

Neutrino decay and long base-line oscillation experiments

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Considering neutrinos as time-like leptons one may estimate the three-body decay probability of muon neutrinos in long base-line accelerator experiments. In the extreme assumption of time-space symmetry the absolute value of the transcendent mass of a muon neutrino is equal to the rest mass of its bradyon partner which is, however, strongly suppressed in measurements using the weak interaction. This decay, neglecting small oscillations or other effects, leads to a strong dependence of the effect on the base-line distance. As a result, few hundred kilometre long baseline experiments might hardly see muon-like events. Total rates of electron-like events from three-body decay are calculated for K2K, MINOS and ICARUS. Shorter base-line experiments able to see clearly the effect of muon neutrino decay are very promising component of long base-line projects.

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I. INTRODUCTION

The solar neutrino problem and the atmospheric anomaly belong to the category of long base-line phenomena using natural neutrino sources. Along with the short base-line oscillation experiments the long base-line projects with man-made neutrino sources are very promising. Among them the recent Chooz project using reactor neutrinos was completed with a negative effect [1]. Most others are planned for installation at high energy accelerators. The K2K project [2] has taken the first run recently and has shown a preliminary first co-event [3]. MINOS at Fermilab-Soudan [4] and ICARUS at CERN-Gran Sasso [5] are in a preparatory stage.

The traditional interpretation of the origin of neutrino anomalies is the oscillation mechanism. Another approach is the possibility of decay of conventional massive neutrinos, which may decay in some mixing components into a singlet majoron and another neutrino, as summarised in Ref. [6]. This decay theory is restricted by very low upper limits on neutrino masses.

As an alternative, we suggested in Ref. [7] a three-body decay mechanism to explain the existing oscillation hints, which considers neutrinos as time-like leptons and where the heavier neutrinos may decay according to the dual principle in the Super-luminous Lorentz Transformation (SLT).

II. TACHYON AND NEUTRINO DECAY

The idea is based on the symmetry between space-like and time-like bradyons, following E. Recami et al. [8], according to which we may suggest that in the

Super-luminous Lorentz transformation the space and the time dimensions should replace each other. As a result, tachyons may travel in a 3-dimension time while moving in an unique space direction. A very severe problem is that no tachyon was ever observed in an experiment. On the other hand, neutrinos are an exception with the following appearances of tachyon properties:

- There is a very high symmetry between neutrinos and space-like leptons which is enhanced in the electro-weak unification;
- Each neutrino has its unique space direction, left or right, described by a definite helicity;
- Neutrinos never stop in a space position, similarly as a space-like particle can never stop in a moment of time-evolution.

A big challenge is the fact that all neutrinos seem to have very small mass, which disturbs the lepton-neutrino symmetry. To solve this problem we assumed in Ref. [7] that neutrinos are realistic tachyons, however due to weak interaction their transcendent masses m being complex have to be strongly suppressed. We suggested that the real part of mass is roughly equal to $\Gamma/2$, where $\Gamma = 2\rho^2 m_0 = 192^{-1} \pi^{-3} G_F^2 m_0^5$ is the decay width of the unstable lepton and m_0 is its rest mass. The imaginary part of tachyon mass is suppressed by the factor ρ , i.e. to the first order by the Fermi constant G_F . This means that the imaginary part may be measured in parity non-conserving experiments by interference of the weak interaction and electro-magnetic or nuclear force. Generally, we may vary the rest mass m_0 as a free parameter to fit the experiments. In this work, however, we prefer to test the first order approximation by making the extreme assumption of time-space symmetry, i.e. that the absolute value of the transcendent mass of a neutrino is equal to

the rest mass of its bradyon partner. For unification of the formalism we extend a similar formula for Γ of unstable leptons to the electron, which does not harm the conclusion that electron neutrinos as time-like electrons

should be stable. As a result, we have got a formalism almost without free parameters in our calculation. In Table I we show the observable transcendent masses of space-like neutrino-tachyons or time-like leptons:

TABLE I. Observable transcendent masses of neutrino-tachyons

lepton-bradyon	electron	μ -meson	τ -lepton
m_0 , MeV	0.51	105.6	1777
τ , sec	$> 1.36 \cdot 10^{31}$	$2.2 \cdot 10^{-6}$	$2.9 \cdot 10^{-13}$
Γ , eV	$< 5 \cdot 10^{-22}$ (\diamond)	$2.5 \cdot 10^{-10}$	$1.9 \cdot 10^{-3}$
$\text{Re}(m^\infty)$, eV	$\leq 2.5 \cdot 10^{-22}$	$1.25 \cdot 10^{-10}$	$9.5 \cdot 10^{-4}$
$-\text{Im}(m^\infty)^2$, eV ²	$1.2 \cdot 10^{-16}$	$1.34 \cdot 10^{-2}$	$1.7 \cdot 10^6$
ρ^2	$5 \cdot 10^{-28}$	$1.2 \cdot 10^{-18}$	$5.3 \cdot 10^{-13}$

(\diamond) a similar formula for Γ of unstable leptons is extended to electron.

In principle, the real part of neutrino masses may cause oscillation effects, however, they are too small to be seen in current experiments. The negligible transcendent masses lead to an experimental fact that neutrinos are always identified as luxons, i.e. particles moving with a speed of light. Now in accordance with the dual principle in SLT, we may consider the muon neutrino as a time-like muon, which is able to decay similarly to the decay of a conventional space-like muon. The decay scheme is:

$$\nu_\mu \rightarrow \nu_e + \mu + e; \quad (1)$$

At variance with the conventional muon decay, due to the energy conservation, the process (1) takes off at a threshold $E_\nu = 106.1$ MeV, similarly to pair production of a gamma ray. It means that muon neutrinos do not decay at rest (DAR) and we are able to observe only the neutrino decay in flight (DIF). In general, we can not warrant the conservation of lepton charge in the decay (1) as neutrinos and leptons may be Majorana ones.

In the three-body decay of a muon neutrino, we may suggest that the muon as well as the positron leave each other from a very short distance ($\leq 10^{-16}$ cm), where the weak interaction dominates the Coulomb attractive force and that they may exist in electric charge (or lepton charge) mixing states as Majorana particles:

$$|\phi_\mu^0(\text{Left})\rangle = \cos \theta_\mu |\mu^+\rangle + \sin \theta_\mu |\mu^-\rangle$$

$$|\phi_e^0(\text{Right})\rangle = -\sin \theta_e |e^+\rangle + \cos \theta_e |e^-\rangle$$

Here we consider only the mixing separately of lepton (muon or electron) charges, but not the flavour mixing as in oscillation theories. In the maximum mixing ($\theta_{\mu,e} = \pi/4$) Majorana leptons are fermions with a defined helicity but electrically neutral, then they may

travel a long way without significant electro-magnetic interaction. At variance with neutrinos, Majorana leptons are space-like particles with a rest mass suggested almost equal to that of the corresponding Dirac leptons. They may regenerate the Dirac component after a definite period because of the lepton (or baryon) asymmetry in our space-like frame. They may also be depolarised while traversing a massive medium. During the process of regeneration or depolarisation the lepton charge is changing, separately, for Majorana electron and muon. However, we suggest that the total lepton charge $L = L_\mu + L_e$ is conserved, that provides the total electric charge unchanged. At the final moment when particles are completely depolarised we may get the normal Dirac components as:

$$|\phi_\mu\rangle = \frac{1}{\sqrt{2}}(|\phi_\mu(\text{Left})\rangle + |\phi_\mu(\text{Right})\rangle) = |\mu^-\rangle;$$

$$|\phi_e\rangle = \frac{1}{\sqrt{2}}(|\phi_e(\text{Left})\rangle - |\phi_e(\text{Right})\rangle) = |e^+\rangle.$$

When the depolarisation time is less than the muon lifetime we may observe not only a positron but also a muon as neutrino decay products. However, if the regeneration period or depolarisation lasts longer the muon lifetime, we may observe only a positron and products of the Dirac muon decay after regeneration or depolarisation. Another possibility is that there is neither regeneration nor depolarisation because of the conservation of lepton charges and Majorana leptons remain almost sterile as dark matter and we can never see them.

Along with the three-body decay there is a possibility of two-body decay as an alternative mechanism. One can consider a well-coupling singlet quasi-muonium consisted of muon-electron pair under attractive Coulomb

interaction at a short distance ($\geq 10^{-16}$ cm), which plays a similar role of the majoron in the two-body decay as described in Ref. [6], however, it does not need flavour mixing. The quasi-muonium, being electrically neutral with a rest mass less than (or close to) the total rest mass of the constituent particles, has to decay into a muon-electron pair after some period, let say, equal to the muon lifetime. The existence of such a quasi-muonium, however, is unlikely as it would be observed in different experiments at accelerators or in atmospheric cosmic rays. Obviously, the two- and three-body decay mechanisms induce different energy spectra of decay products, providing a means to identify the actual decay mode.

In the next section we show that the three-body decay in the first order approximation (without any free parameter) may give a satisfactory interpretation of all short base-line oscillation experiments at nuclear reactors as well at accelerators. As a next step we predict some consequences of this decay mode for long base-line oscillation experiments.

III. INTERPRETATION OF SHORT BASE-LINE OSCILLATION EXPERIMENTS

We summarise here our results in Ref. [7] as a demonstration of the suggested mechanism to interpret short base-line oscillation experiments carried out at accelerators (including LSND, KARMEN and NOMAD), as well as at nuclear reactors (including Bugey and the first short base-line Chooz).

The positive effects of LSND have been interpreted as oscillations of the muon anti-neutrino produced in muon decays at rest (DAR), and oscillations of the muon neutrino produced in muon decays in flight (DIF). In both cases muons are decay products of the pions produced at the target A6. Instead of this oscillation interpretation, in our Ref. [7] the LSND effects were explained by the decay in flight of muon neutrinos mainly from "minor" targets A1 and A2 but not by the decay at rest of those from the major target A6. The last one (A6) contributed only about 20% in the total effects of decay in flight. In Fig. 1 are shown our calculated spectra of cc-positrons and cc-electrons produced in interactions of electron anti-neutrinos and neutrinos as products of muon neutrino decay with hydrogen and carbon nuclei in the fiducial volume.

The calculated spectra are integrated over the range from 36 to 60 MeV for cc-positrons and from 60 to 200 MeV for cc-electrons, which give 9.9 positrons and 37.5 electrons. Comparing with LSND data which give $22.0 \pm 8.5 \pm 8.0$ cc-positrons and $18.1 \pm 6.6 \pm 4.0$ cc-electrons, our results are thus in an acceptable agreement with them.

In KARMEN as a sister project of LSND only decays at rest (DAR) of pions and muons were taken into account, therefore all muon neutrinos had an energy below threshold (106.1 MeV) and could not decay.

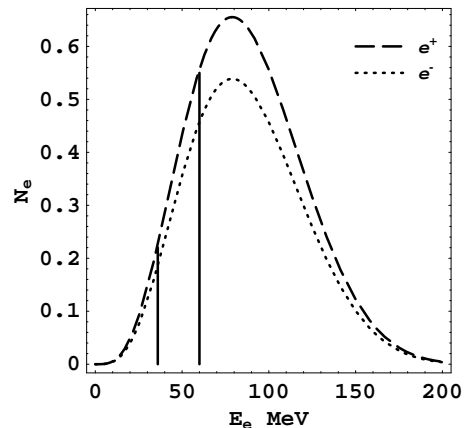


FIG. 1. Spectra of cc-events of LSND

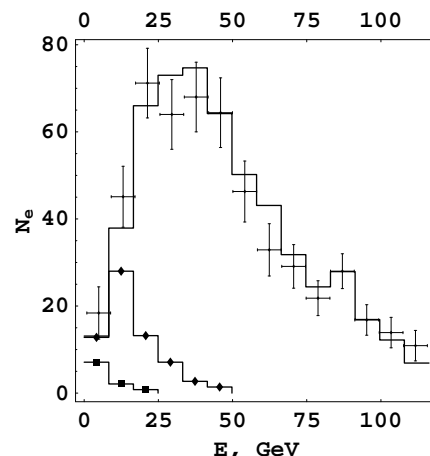


FIG. 2. Decay contribution in the cc-spectrum NOMAD

We have calculated the neutrino decay at high energy in the NOMAD experiment following the same procedure as for LSND. The fiducial volume containing about $1.5 \cdot 10^{30}$ nucleons and the initial muon neutrino spectrum were taken from Ref. [9]. The νN -cross-section is proportional to energy as $0.78 \cdot 10^{-38} E_\nu$ (GeV) cm^2 . In Fig 2 we show the total spectrum of cc-electrons, where the dash-line is a Monte-Carlo simulation without oscillation; the calculated contribution of the neutrino decay (box-line) consists only of 10.0 events in the range of 1 – 20 GeV, namely 5 times less than expected from oscillation (star-line). This is to conclude that our decay calculation is in a good agreement with the data of NOMAD. However, the poor statistics and low energy resolution in the lowest range of 1 – 20 GeV do not allow to separate the effect of neutrino decay in flight (DIF) from the background.

Concerning electron (anti-) neutrinos, they are suggested stable as time-like electrons (positrons), and certainly can not decay. As a result, oscillation experiments

at nuclear reactor producing only electron anti-neutrinos could not see any effect. The recent attempt as a reactor long base-line project at Chooz is not an exception [1]. For the solar anomaly concerning electron neutrinos, we have proposed in Ref. [10] a qualitative interpretation by a total depolarisation of the pseudo-spin of time-like electrons passing through a thickness of dark plasma matter. It could give in the first order approximation a roughly 50% deficit of the expected solar neutrino flux which is in agreement with the averaged experimental data $R = 0.46 \pm 0.06$.

IV. ESTIMATION OF MUON NEUTRINO DECAY AT ACCELERATOR LONG BASE-LINE PROJECTS

In the present section we deal with the three-body decay of muon neutrinos at long base-line experiments, compared to oscillation predictions. For this purpose we consider the projects: i/ K2K at KEK-Super-K currently running [2]; ii/ MINOS at Fermilab-Soudan, already approved and in preparation [4] and iii/ ICARUS at CERN-Gran Sasso waiting for approval [5].

The decay in flight of muon neutrinos are calculated

using the same parameters as for muons (decay width Γ or life-time τ_μ , rest mass m_0) and the equation for decay probability reads:

$$P_d = 1 - \exp\{-m_0(\text{GeV})/(\tau_\mu c) L(\text{km})/E_\nu(\text{GeV})\}; \quad (2)$$

The two-neutrino oscillation probability is calculated using the well-known formula:

$$P_{os} = \sin^2 2\theta \sin^2\{1.27 \Delta m^2(\text{eV}^2) L(\text{km})/E_\nu(\text{GeV})\}; \quad (3)$$

Here we use the most favourable parameters of the LSND [11] for the $(\nu_\mu \rightarrow \nu_e)$ oscillation $(\sin^2 2\theta, \Delta m^2) = (6.10^{-3}, 19\text{eV}^2)$ and also those of the Kamiokande atmospheric anomaly [12] for the $(\nu_\mu \rightarrow \nu_\tau)$ one: $(\sin^2 2\theta, \Delta m^2) = (0.95, 5.9 \times 10^{-3}\text{eV}^2)$. Table II reviews the estimation of decay and oscillation probabilities of muon neutrinos from the long base-line experiments at a mean energy averaged over all a spectrum of each neutrino source. In this table we give not only long base-line distances but also the base-line of the companion short distance detectors. Included are: i/ the KEK front detector; ii/ COSMOS at Fermilab, and iii/ JURA at CERN.

TABLE II. Calculation of decays and oscillations probabilities of muon neutrinos

Project/Detector	E_ν (GeV)	L (km)	P_{os} LSND	P_{os} Atm.	P_d
K2K/Super-K	1.5	250	1.10^{-3}	0.89	≈ 1.0
K2K/Front Det.	1.5	300 m	3.410^{-5}	2.110^{-6}	0.02
Fermilab/MINOS	11.	732	8.610^{-3}	0.22	≈ 1.0
Fermilab/COSMOS	11.	500 m	4.810^{-3}	1.110^{-7}	7.210^{-3}
CERN/ICARUS	30.	730	5.710^{-4}	0.03	0.98
CERN/JURA	30.	17	4.810^{-3}	1.710^{-5}	0.09

We see from Table II that the LSND parameters produce very small effects everywhere, while the Kamiokande parameters give significant oscillation in the long base-line detectors, but negligible effects in the companion short distance detectors.

The neutrino decay predicts very large effects on a far distance that all long base-line detectors hardly observe muon-like events. At Super-K and at MINOS almost all muon neutrinos have to decay before reaching the detectors. Only about 2% of the muon neutrinos subsist at ICARUS. In Fig. 3 we illustrate different behaviours of the decay (Fig. 3a) and oscillation probabilities as functions of muon neutrino energy in the K2K long base-line project. For the oscillation we have taken again

parameters from both experiments LSND (Fig. 3b) and Kamiokande (Fig. 3c). In the next presentation, we take into account of the oscillation only the Kamiokande parameters.

Instead we may see muon-like events at short distance detectors, where the amounts of electron neutrinos as neutrino decay products may be significant, particularly at JURA, this proportion amounts to 9% of the total neutrino beam. At variance with oscillations, electron neutrinos from neutrino decays have in average only one third of the initial muon neutrino energy as the calculated electron neutrino spectrum (box-dash line) illustrated in Fig. 4 for K2K. For comparison there is shown a spectrum (diamond-dot line) of tauon (or electron) neutri-

nos from the $\nu_\mu \rightarrow \nu_\tau(\nu_e)$ oscillation, which repeats the shape of the initial muon neutrino spectrum (histogram). In Fig. 5 we show the corresponding calculated spectra of electron-like events from the neutrino decays (histogram) and from the oscillations (box-dash line). In the calculation we use the $\nu_e N$ cross-section as in [13] for K2K, and a simplified cross-section at higher energy for MINOS as $\sim C \cdot 10^{-38} E_\nu$ (GeV) cm^2 , where $C = 0.78$ for electron-like events and $C = 0.62$ for muon-like ones. We see that the spectra of electron-like events are very different each other for the neutrino decay and for the oscillation. Particularly, the decay spectrum is softened significantly in variance with the oscillation spectrum.

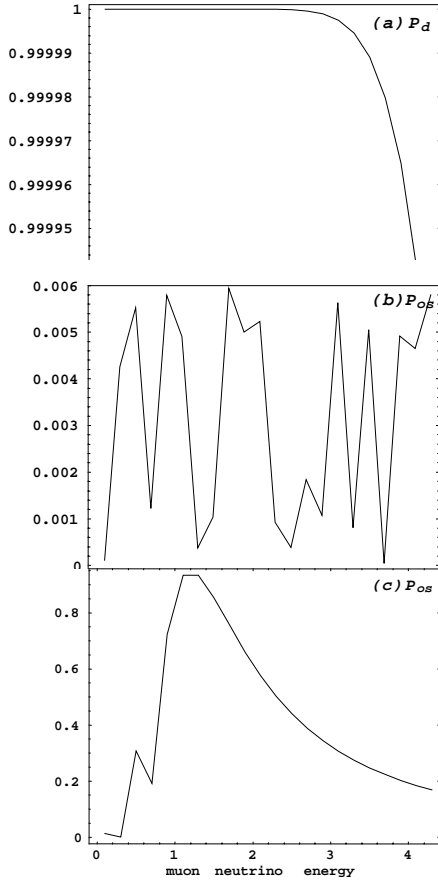


FIG. 3. K2K probabilities of decay (a) and oscillation: LSND- (b) and Kamiokande- (c).

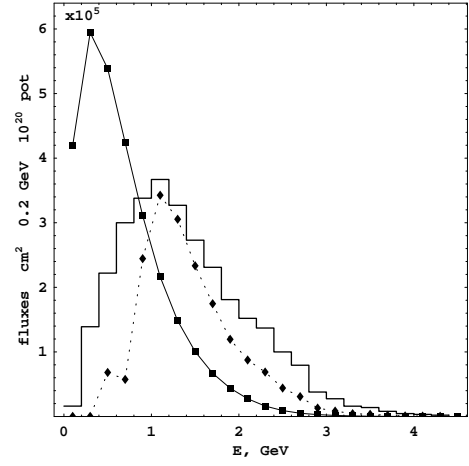


FIG. 4. K2K Muon and electron neutrino spectra.

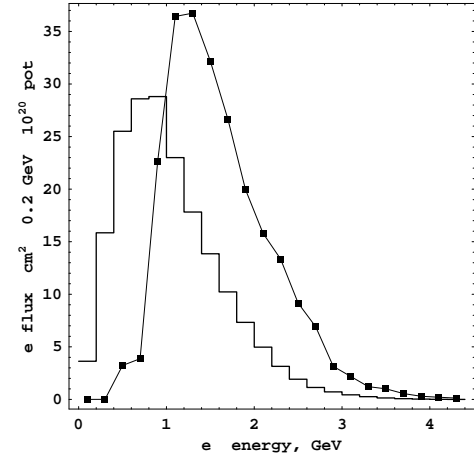


FIG. 5. K2K cc-electron spectra.

In Table III we summarise the total rates of cc-events integrated over the calculated spectra of cc-events at K2K and MINOS.

TABLE III. Total rates of cc-events for 10^{20} protons on target

Project/Detector	Fiducial volume, kton	osc. surviving cc-muons	oscillation cc-electrons	decay cc-electrons
K2K/Super-K	22	107.0	235.6	187.4
Fermilab/MINOS	10	7624.0	1884.7	5116.1

For 10^{20} protons on target (p.o.t.) at K2K, if the muon neutrino decay works, only 187 cc-events will be collected and if the particle identification (PID) works well only electron-like events, but no muon-like events will be seen. Here we cannot exclude the possibility that the electron neutrinos are Majorana. In this case only the Dirac component may be detected, as in the solar neutrino flux and, as a result, the total amount of electron-like events may be decreased up to 50% (for the maximum mixing [10]).

For the oscillation mechanism there are different possibilities: i/ when the ($\nu_\mu \rightarrow \nu_e$) version works, we may have more electron-like events (236) from the oscillation and an amounts of muon-like ones (107) from the survivors of the initial muon neutrino spectrum; ii/ when the ($\nu_\mu \rightarrow \nu_\tau$) version works, we may see the same amount of muon-like events from the surviving muon neutrinos, however the rate of cc-events from the tauon neutrinos decreases significantly, due to the high threshold of the $\nu_\tau N$ reaction and the low ratios of tauon decay into muon or electron, which are 17.9% and 17.4%, respectively [14].

The first run of K2K at Super-K has seen the first cc-event [3]. We have to wait for the next run in year 2000, for sufficient statistics before making any definite conclusion. According to Table III, MINOS will give more statistics to identify the origin of the oscillation hints.

V. CONCLUSION

In the Super-K long base-line detector we expect to identify muon-like events from electron-like ones as a criteria to test the three-body decay of muon neutrinos. The shape of the spectra and the quantity of cc-events are also sensitive to the origin of the oscillation hints.

If the decay mechanism works, we suggest to the next long base-line experiments to use intensively the shorter base-line detectors. The optimal condition for observation is to get significant amounts of neutrino decays to see electron-like events, not to harm the intense flux to see also a proportion of muon-like events, that a decay rate larger than say 20% is desirable. It leads to a ratio $L(km)/E_\nu(GeV) = 1.4$ and the base-line $L(km)$ equal to: 2.1; 15.3 and 41.8 km respectively, for the KEK front detector, COSMOS and JURA. The experiments with

modified shorter base-line detectors might collect a significant statistics for a short period. For example, 0.5 kton fiducial volume of the KEK front detector at the distance 2.1 km may see 10^4 muon-like and about $(4 - 8) \times 10^3$ electron-like events for 10^{20} p.o.t.

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